

2. HYDRAULIC DESIGN

The hydraulic design of any structure is based on the purposes or objectives it is to accomplish. The purposes for which chutes are used have been listed. The explicit objective of chutes is to convey all discharges equal to or less than a given design discharge Q_r from one elevation to a lower elevation in a manner which will not cause erosion between the two elevations. To accomplish this objective, the various component parts of the chute need to be properly proportioned to perform certain functions. These functions and the hydraulic design of the components are considered in this part. Sometimes chutes are designed to fulfill additional objectives besides the one explicitly stated above.

Functions of Inlets. The inlet of a chute has several functions. They are:

- a. Convey and guide all discharges equal to or less than a given design discharge to the vertical-curve section or steep, paved channel in a manner that will not cause any appreciable waves in the steep channel of the chute.
- b. Provide a positive cutoff of flow by piping under and around the chute channel.
- c. Permit all discharges equal to or less than a given design discharge to pass safely through the inlet between the spillway crest and top of the sidewalls.

Further explanatory remarks are made concerning these functions before the hydraulic design of the three types of inlets are considered.

Standing Waves. Flow of water through the inlet to the steep, vertical-curve section passes from subcritical to supercritical. (See Engineering Handbook, Section 5, Hydraulics.) A phenomenon known as "standing waves" can occur when flow is supercritical. The standing waves can attain heights several times the average depth of flow and persist downstream, sometimes almost undiminished in height, through the length of the steep channel. Standing waves can occur when any one of the following conditions exists in the steep channel:

- a. The walls of the steep channel are not parallel; i.e., the walls converge or diverge.
- b. The walls of the steep channel are not straight; i.e., the chute is curved in a longitudinal direction.
- c. The sidewalls of the steep channel are not vertical; i.e., the sidewall has a side slope.
- d. The bottom of the steep channel is not level in a direction perpendicular to the axis of the channel; i.e., the channel bottom has a cross slope.
- e. The direction of flow in the steep channel is not parallel to the sidewalls.
- f. The flow has an appreciably unequal distribution of velocities (or energy) in a channel cross section.
- g. The flow has an appreciably unequal distribution of discharge in channel cross section.
- h. An irregularity or obstruction exists in the channel.

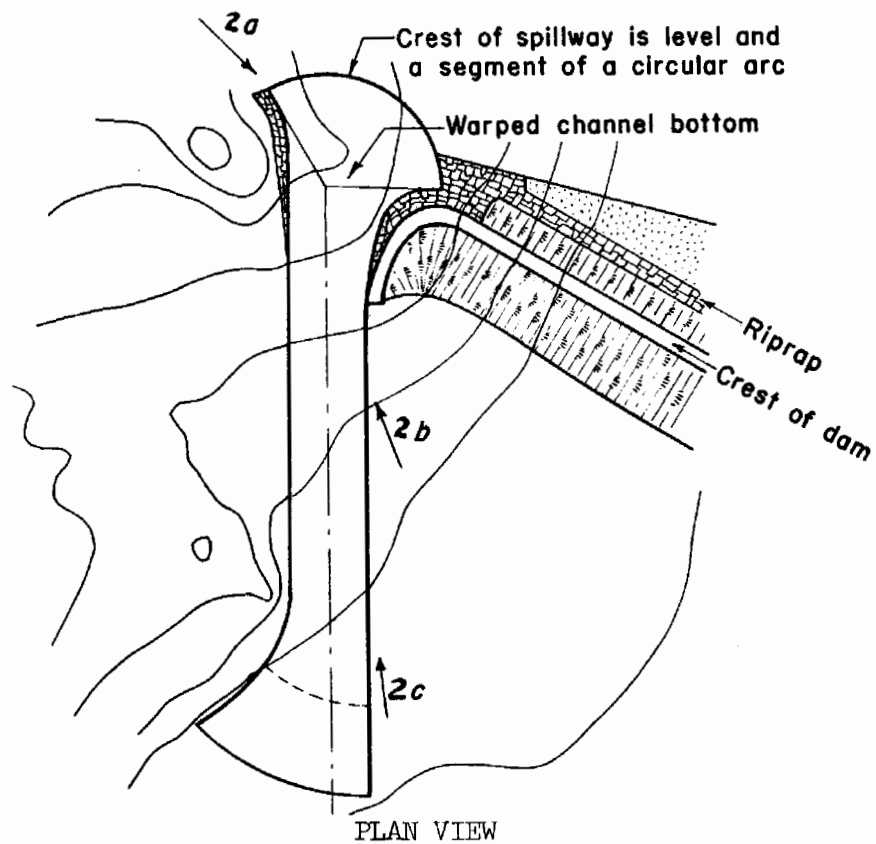
An example of a standing wave is shown by several photographs. Figure 2 shows a plan view of a reinforced concrete spillway and the approximate directions in which subsequent photographs were taken. Observe that the spillway crest is level and is a segment of a circular arc. All flow downstream from the crest is supercritical. Figure 2a shows the flow of water over the crest. The head on the crest is approximately 3.5 ft and the discharge over the crest is approximately 4000 cfs. The direction of flow at the crest is variable and at any point is in the direction toward the center of curvature of the crest. Figure 2b shows a standing wave reflected diagonally from the far wall. Observe that no flow occurs on a small area along the near wall. Every condition except conditions (c) and (h), page 2.1, contributes to the development of this standing wave. The channel walls immediately below the spillway crest are neither parallel nor straight. The channel bottom immediately below the crest is a warped surface. Flow over the crest is not in a direction parallel to the sidewalls. The discharge per foot length over the crest is uniform, but is not presented to the steep channel uniformly; thus, unequal distribution of velocities and discharge are present in the channel. Figure 2c shows the poor flow conditions through the channel and overtopping of the left wall by a discharge which is less than 30 percent of the design discharge.

A sharp corner in the sidewall or irregularity or obstruction in the channel where supercritical flow exists will have no effect on flow upstream from any such obstruction as long as the obstruction does not induce subcritical flow. The effect of any such obstruction in supercritical flow is to cause a standing wave to occur diagonally from the obstruction downstream to the sidewall. This standing wave will then be reflected diagonally downstream again and again from the sidewalls. These statements are made on the assumption that no other obstructions are placed to "cancel out" the standing wave. It is not to be implied that steep channels having curvature in their alignment or having a cross slope in their bottoms cannot be designed to function properly. In general, the design of such channels should be checked by hydraulic model studies.

General Criteria to Accomplish Functions of Inlets. The first listed function of the inlet can be accomplished if the inlet conveys the water so that velocity and discharge distribution are uniform at the entrance to the vertical curve, and the direction of flow is parallel to the axis of the chute. Uniform velocity and discharge distribution at the entrance of the vertical curve section require that both the water surface and floor at this section be level transversely. Uniform discharge distribution requires that this section be rectangular. The transverse water-surface profile can be made level by one of the following methods:

- a. Providing sufficient length of a level prismatic channel upstream from this section. (See ES-82, page 2.13, for example.)
- b. Providing a level cross weir of sufficient height at this section. (See ES-85, page 2.113, for example.)

Flow by piping can be prevented by construction of an adequate anti-seep collar.



Arrows indicate directions photographs were taken.

FIGURE 2

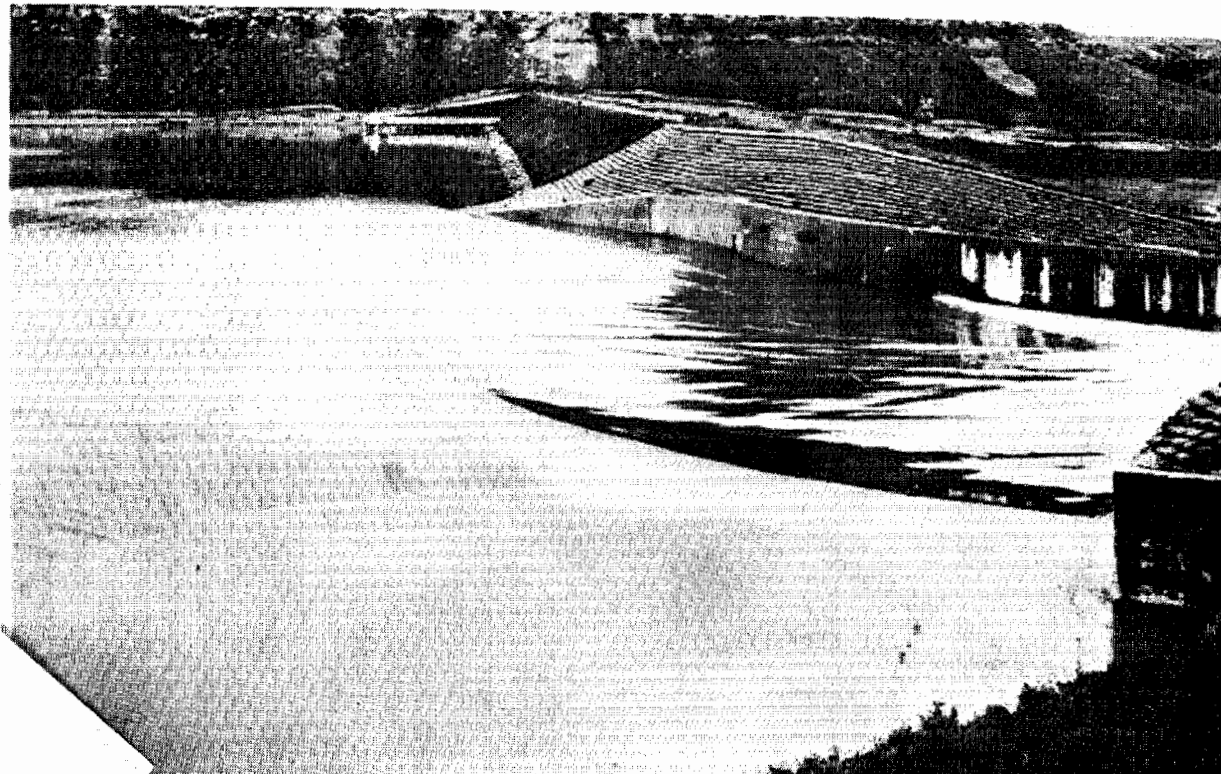


FIGURE 2a



FIGURE 2b



FIGURE 2c

All the factors presented by the third function are not recognized by some engineers. Ignoring that the distance between the elevation of the spillway crest and a maximum water-surface elevation at the inlet is a determinable quantity can lead to appreciably higher structural costs by improper choice of inlet type or chute dimensions. Selection of the type of inlet is not an arbitrary choice nor is the width of the chute. The type of inlet is determined on the factual basis of:

- a. Functional uses
- b. Physical conditions of a site
- c. Economy

A detailed explanation of methods to determine the type of inlet and its dimensions is given in part 3. A few limited explanatory remarks in the form of examples suggesting some of the elements which are involved in this determination will be made here.

Some inlets are designed for additional functional uses. For example, a culvert inlet is used to provide a crossing for vehicles, equipment, pedestrians, or livestock. As will be seen later, culvert inlets may be used for other reasons.

An illustration of how the physical conditions of a site determines the type of inlet follows. A site may require that the head over the crest be restricted to prevent inundation of certain areas or objects. (See page 2.6 for definition of head over the crest.) Whenever the head over the crest is reduced, the length of the inlet crest must be increased to prevent lowering the capacity of the inlet. A physical condition which requires that the head over the crest be small may determine the type of inlet and its dimensions. A physical condition of this type might dictate that a box inlet be used.

In another example, a site which requires that the spillway be placed adjacent to or in a steep bank might dictate the use of a side-channel spillway.

An example in which economics might dictate that a box inlet be used follows. Frequently a chute is associated with a high or long embankment. The amount of head required over the crest of the inlet for a given design discharge has an important influence on the cost of the associated embankment. The amount of head over the crest of the inlet can always be decreased without decreasing the inlet capacity by increasing the length of the crest. When the head over the crest is decreased, the height of the embankment can be decreased by the same amount. If the associated embankment yardage is of considerable height or length, a large decrease in embankment yardage is made by choosing a smaller head over the crest. The saving in cost of embankment yardage may be greater by this choice than the cost of additional concrete yardage required for a chute with a box inlet.

One other example will be given which involves the use of a box-culvert inlet. Spillways of reservoirs having large surface areas must be designed with wave freeboards. When this freeboard becomes large, it might be more economical to build a box-culvert inlet instead of a box inlet or a straight-culvert inlet.

All chutes should be designed with the proper type of inlet and a set of dimensions in accordance with the basic facts presented by the particular site. These basic facts are a matter for field determination.

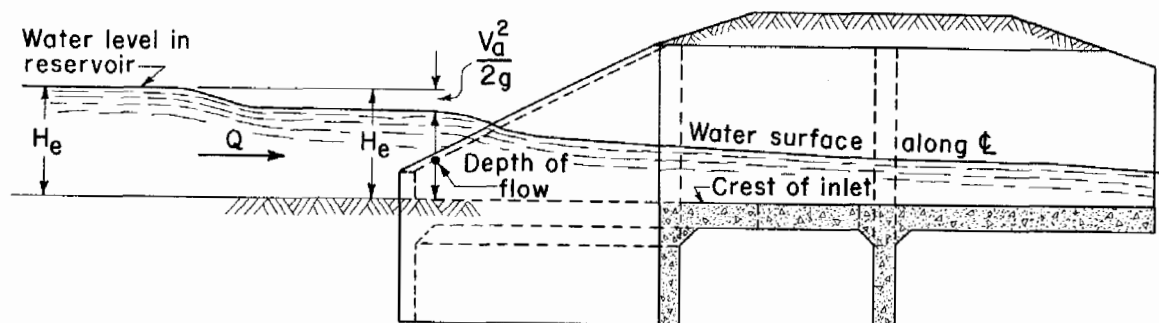


FIGURE 3

Head over the crest of an inlet is the sum of the depth of water above the crest and the velocity head at the section near the entrance of the inlet at which the head over the crest H_e is measured. (See Fig. 3.) This head is the specific energy head referenced to the crest and is measured in feet. Spillways for reservoirs have a head over the crest H_e equal to the difference in elevation of the water surface in the reservoir near the entrance of the inlet and the elevation of the crest if friction losses between the reservoir and inlet entrance are negligible. The head over the crest corresponding to the design discharge Q_r (see part 1) is the design head over the crest h_r .

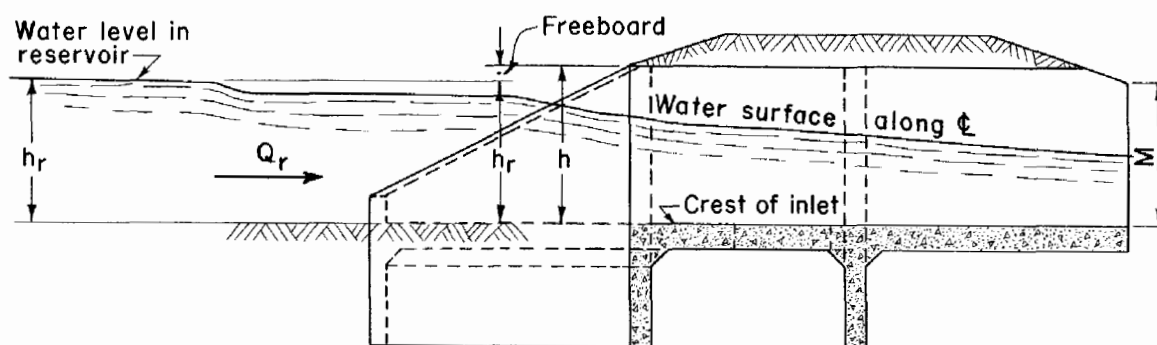


FIGURE 4

Freeboard of an inlet is the difference in the sidewall height h above the crest and the design head h_r over the crest of the inlet. (See Fig. 4.) It is measured in feet and is a safety factor to prevent overtopping of the inlet. The overtopping could be a result of one or more causes. Among the causes are wave action, inability to predict closely the capacity of the inlet, decreased capacity of the inlet due to some unpredicted condition (see definition of capacity, page 2.7), and a larger discharge requirement than the design discharge Q_r due to inability to predict runoff with precision.

Since it is possible to estimate wave heights by Stephenson's equation or a modification of that equation, the freeboard requirement for wave action will be considered separately from freeboard requirement for other causes.

These other causes are common to all structures. The freeboard requirement of structures in which wave action is anticipated will be the sum of the freeboard requirement for wave actions and the freeboard requirements for the other causes. Freeboard requirement for these other causes is known as no-wave freeboard.

Recommended No-wave Freeboard. Where no wave action is anticipated, it is convenient to express freeboard in terms of design discharge. It is logical that the freeboard should be dependent on the design discharge Q_R and the vertical drop Z from the crest of the inlet to the floor of the outlet. The recommended freeboard f_R for inlets having no wave action expressed in units of discharge is

$$f_R = (0.20 + 0.003 Z) Q_R = Q_{mi} - Q_{si} \quad 2.1$$

where Q_R = design discharge in cfs

Z = vertical drop from the crest of the inlet to the floor of the outlet in ft

f_R = recommended freeboard expressed as a discharge in cfs

The choice of this safety factor, or freeboard, is somewhat an arbitrary quantity and for this reason, as well as convenience, capacities of various component parts of the chute will be given without freeboard.

Recommended Wave Freeboard for Inlets. For inlets in which wave heights are approximated, an additional freeboard is required. The wave heights may be approximated by one of the four formulas, 3.8, 3.9, 3.10, or 3.11, page 3.8, Engineering Handbook, Section 11, Drop Spillways. The recommended total freeboard for inlets of chutes is the sum of the approximated wave heights and the freeboard recommended for inlets in which no wave action is anticipated.

Capacities With and Without Freeboard. (See next section, Symbols.) The distinction in the meanings of the words "design discharge," "capacity," and "required capacity" is important. The design discharge Q_R is the discharge that the inlet (or chute) is required to convey and is determined by hydrological and reservoir-routing considerations. The capacity Q_{si} of the inlet is the discharge that the inlet is capable of conveying with the recommended freeboard (see page 2.11) and is determined in part by the dimensions of the inlet. This capacity will be used infrequently in this Chute Spillway Section of the Handbook. The capacity without freeboard Q_{mi} of the inlet is the discharge that the inlet is capable of conveying without freeboard. It is greater than the capacity Q_{si} and is determined solely by the dimensions of the inlet. The difference in the capacity Q_{si} of the inlet with the recommended freeboard and the capacity without freeboard Q_{mi} is the recommended freeboard of the inlet expressed in discharge cfs instead of feet. The required capacity without freeboard Q_{fr} is the design discharge Q_R increased by the recommended freeboard expressed as a discharge. The required capacity without freeboard becomes

$$Q_{fr} = Q_R + f_R$$

or by Eq. 2.1

$$Q_{fr} = (1.20 + 0.003 Z) Q_R \quad 2.2$$

where Q_{fr} = required capacity without freeboard in cfs
 Q_r = design discharge in cfs
 Z = vertical distance from crest of inlet to floor of outlet in ft

The chute spillway is designed to have a capacity without freeboard as great as the required capacity without freeboard Q_{fr} ; thus, the capacity without freeboard Q_{mi} , Q_{mv} , Q_{mc} , and Q_{mo} of the various component parts will all be at least as large as Q_{fr} . This gives each component part approximately the same factor of safety. The capacity without freeboard usually will be slightly larger than the required capacity, because only component parts of even dimensions are considered. A component part of a given size or set of dimensions will have associated with it a maximum discharge which it is capable of conveying without freeboard. This maximum discharge is the capacity without freeboard Q_m of that component part which is equal to or slightly greater than the required capacity without freeboard Q_{fr} , because the next smaller component part has a capacity without freeboard less than Q_{fr} .

Symbols. The symbol Q with subscripts is being used for both discharge and capacity. For instance, the symbol Q with the subscript m is used to designate the capacity of the chute without freeboard Q_m . The capacity of the chute without freeboard is dependent upon the size of the chute or on the various dimensions of the chute. The subscript i is added to the subscript m to designate the capacity of the inlet without freeboard Q_{mi} . Likewise, the subscript v is added to denote the vertical curve section, the subscript c to designate the channel, and the subscript o is added to m to signify the outlet. For example, Q_{mi} , Q_{mv} , Q_{mc} , Q_{mo} , and Q_m are respectively the capacity without freeboard of the inlet, the vertical curve section, the channel, the outlet, and the chute as a whole. The capacity without freeboard of the chute as a whole Q_m is equal to the smallest of the values Q_{mi} , Q_{mv} , Q_{mc} , and Q_{mo} .

The symbol Q_s designates the capacity of the chute with the recommended freeboard. The value of Q_s is dependent on the dimensions of the chute and the recommended freeboard. The subscripts i , v , c , and o will have the same meaning as before and Q_{si} , Q_{sv} , Q_{sc} , Q_{so} , and Q_s are respectively the capacity with the recommended freeboard of the inlet, vertical curve section, channel, outlet, and the chute as a whole. The capacity with the recommended freeboard of the chute Q_s is equal to the smallest of the values Q_{si} , Q_{sv} , Q_{sc} , and Q_{so} . Observe that an inlet with given dimensions will have a definite capacity without freeboard regardless of the recommended freeboard. The capacity of this inlet with the recommended freeboard is dependent not only on the dimensions of the inlet but also on the recommended freeboard.

The dimensions of the straight inlet, namely h , M , and W will be used to determine the capacity without freeboard of the inlet Q_{mi} . The dimensions M , N , J , and W will be used to determine the capacity without freeboard of the vertical curve section. The dimensions N and W are used for determining Q_{mc} ; J , L_B , Z , and W are used to determine Q_{mo} . These determinations will be given where the discussions of the various component parts are made. Since the width of the chute W is used in determining the capacity

without freeboard for each of the component parts, the symbol q will be used to denote the discharge per foot width. Likewise, the symbols q_{mi} , q_{mv} , q_{mc} , q_{mo} , and q_m are used to designate respectively the capacity without freeboard per foot width of the inlet, vertical curve section, channel, outlet, and the chute as a whole.

The discharge Q through a chute can be any quantity ranging in value from zero to the capacity without freeboard Q_m . If Q is greater than Q_m , then the chute is overtopped and the discharge relationships given for component parts are not applicable.

The design discharge Q_r is that discharge the chute and each of its component parts is required to convey with the recommended freeboard. The required capacity without freeboard Q_{fr} of the chute and each of its component parts is obtained by use of Q_r in Eq. 2.1. Thus the capacity without freeboard of each of the component parts Q_{mi} , Q_{mv} , Q_{mc} , and Q_{mo} will be equal to or slightly larger than the required capacity without freeboard Q_{fr} because only even dimensioned component parts are considered in evaluating Q_{mi} , Q_{mv} , Q_{mc} , and Q_{mo} .

The definition of the few additional symbols will be considered at their first appearance.